Climatology of the Ionospheric Scintillations over the Auroral and Cusp European Regions

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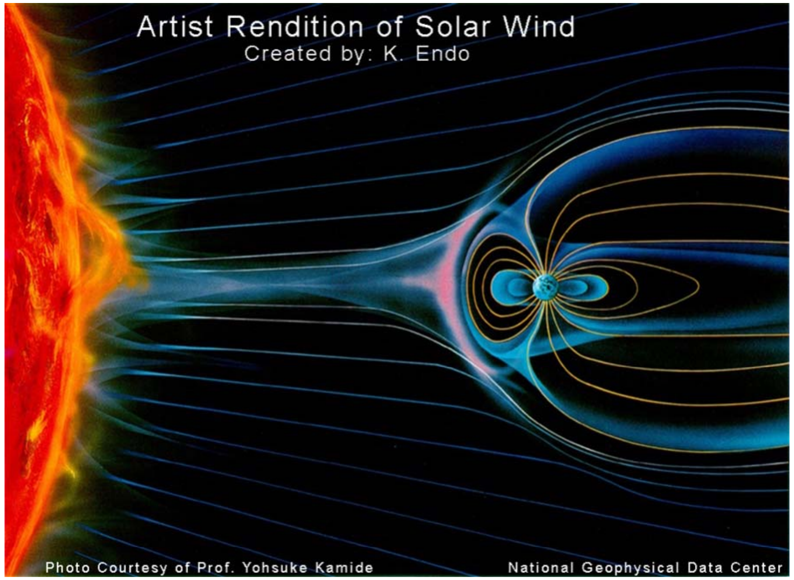
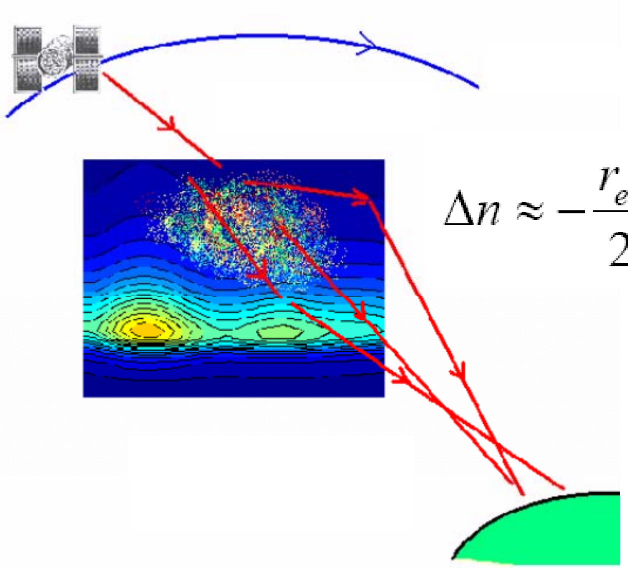
Summary

- *Introduction*
- *Data*
- *Method*
- *Results and discussion*
  - σ_{φ} *maps*
  - S_4 *maps*
- *Remarks*

Introduction (I)

- Perturbations from the outer space cause turbulences of the ionosphere
  - Creation of small scale irregularities (cm to m)
  - Enhancements or depletions of the electron density
  - Random fluctuations of the refractive index
    - Distortion of the original wave front
- Diffraction effects on the satellites signals
- Fluctuations in the carrier frequency can be analyzed to investigate the physical processes causing scintillation
  - Phase fluctuations
  - Amplitude fluctuations





$$\Delta n \approx -\frac{r_e \lambda^2}{2\pi} N$$

Introduction (II)

AIM

Develop a "scintillation climatology" over the Northern Europe

– combining the information coming from auroral to cusp latitudes.

DATA

Scintillation data from *4 GISTM* (GPS Ionospheric Scintillation and TEC Monitor) receivers

- NovAtel OEM4 dual-frequency
- 50 Hz data

WHERE

Geographic latitudinal range 44 °-88° N

– Original and novel statistics over such a wide range of latitudes for GPS signals.

WHEN

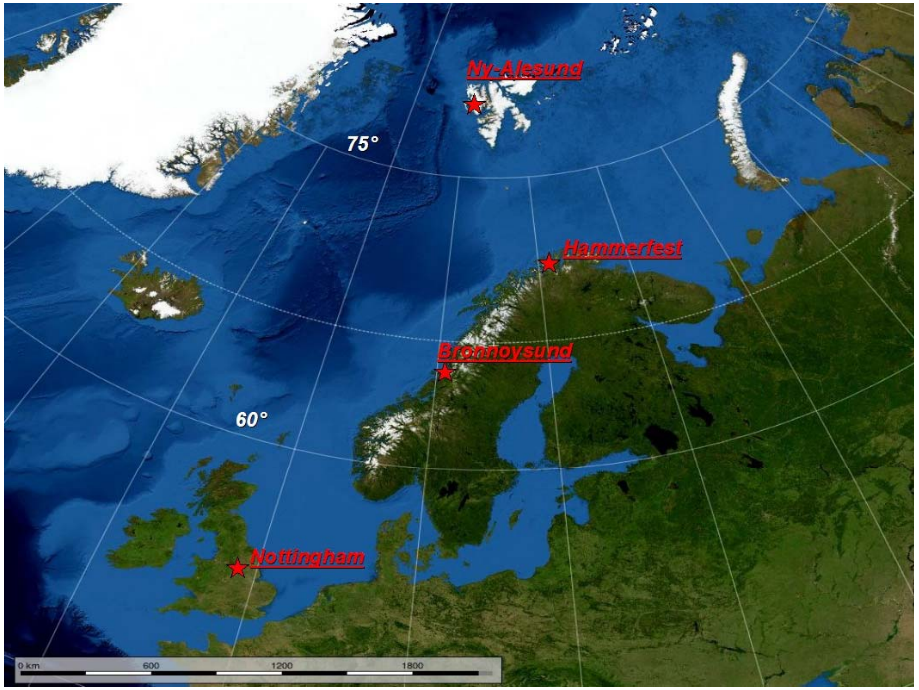
October, November and December 2003

– 2 intense magnetic storms: 30-31 October and on 20-21 November

– important scintillation events

METHOD

Scintillation occurrence maps



Station	ID	Lat (°)	Lon (°)
Ny-Ålesund	NYA	78.9°N	11.9°E
Hammerfest	HAM	70.7°N	23.7°E
Brønnøysund	BRO	65.5°N	12.2°E
Nottingham	NOT	52.9°N	1.2°W

Data

- Scintillation indices computed over 60 seconds from L1 (1.57 GHz)
  - σ_φ: std dev of the detrended phase of the carrier frequency
  - S_4: std dev of the received power normalized by its mean value
- Reducing tracking errors
  - α_{elev} > 15° for both indices.
- Vertical quantities

Total amount of data points is of the order of 1 million per station

Only a significant data gap in Dec in HAM and BRO

Method

- ***Maps of percentage occurrence*** of the scintillation indices
  - Mlat vs MLT
  - Sub-ionospheric point (350 km)

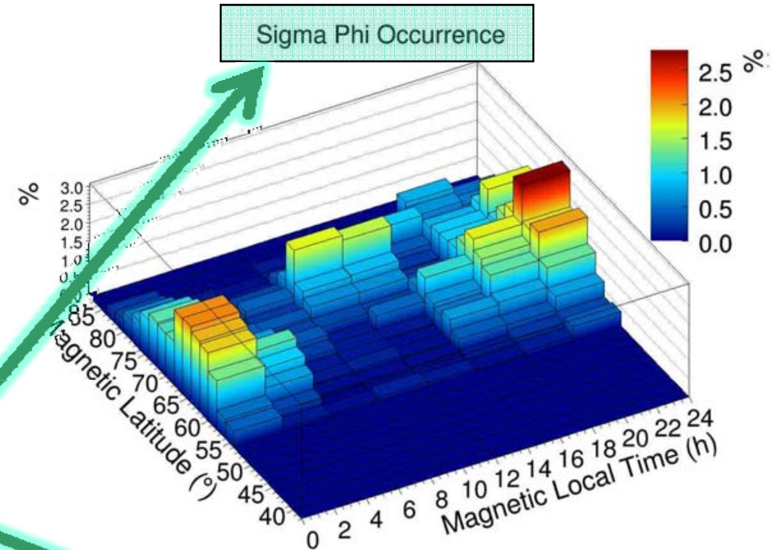
ID	Mlat (°)	Mlat Range (°)
NYA	76.0	68-84
HAM	67.2	58-76
BRO	62.6	54-72
NOT	54.8	40-58

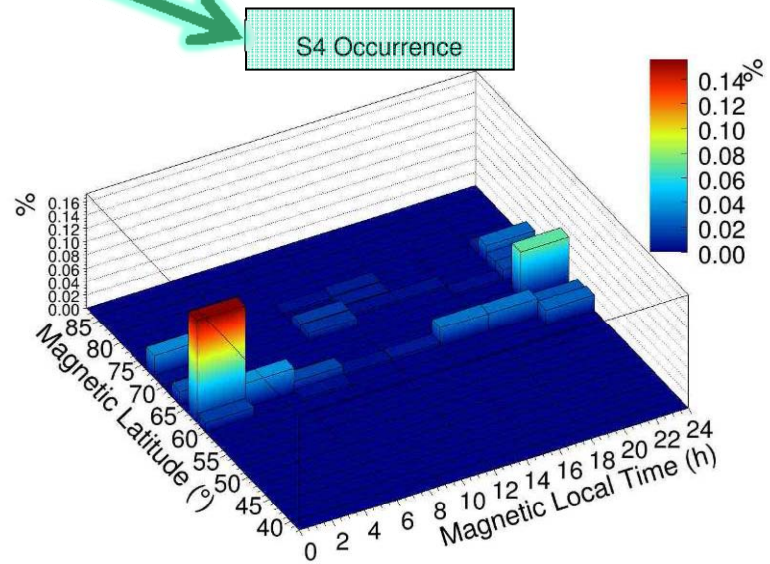
- Percentage occurrence
  - $\frac{N(S_4 or \sigma_\varphi > threshold)}{N_{tot}}$
  - evaluated for each bin
    - 1 bin = 3h MLT x 2° Mlat
- Thresholds:
  - 0.25 radians for σ_φ
  - 0.25 for S_4
- For each map bin the statistical accuracy $R_{\%} = 100 \times \frac{\sigma(N_{tot})}{N_{tot}} = \frac{100}{\sqrt{N_{tot}}}$
  - $R_{\%} < 2.5\%$

- Maps realized for different geomagnetic conditions
  - Geomagnetic characterization through ***K_p*** index
    - A day is assumed to be *quiet* if 50% of K_p values is less or equal to 4.
    - About half of the days in each month is found to be *disturbed*.

Results and Discussion

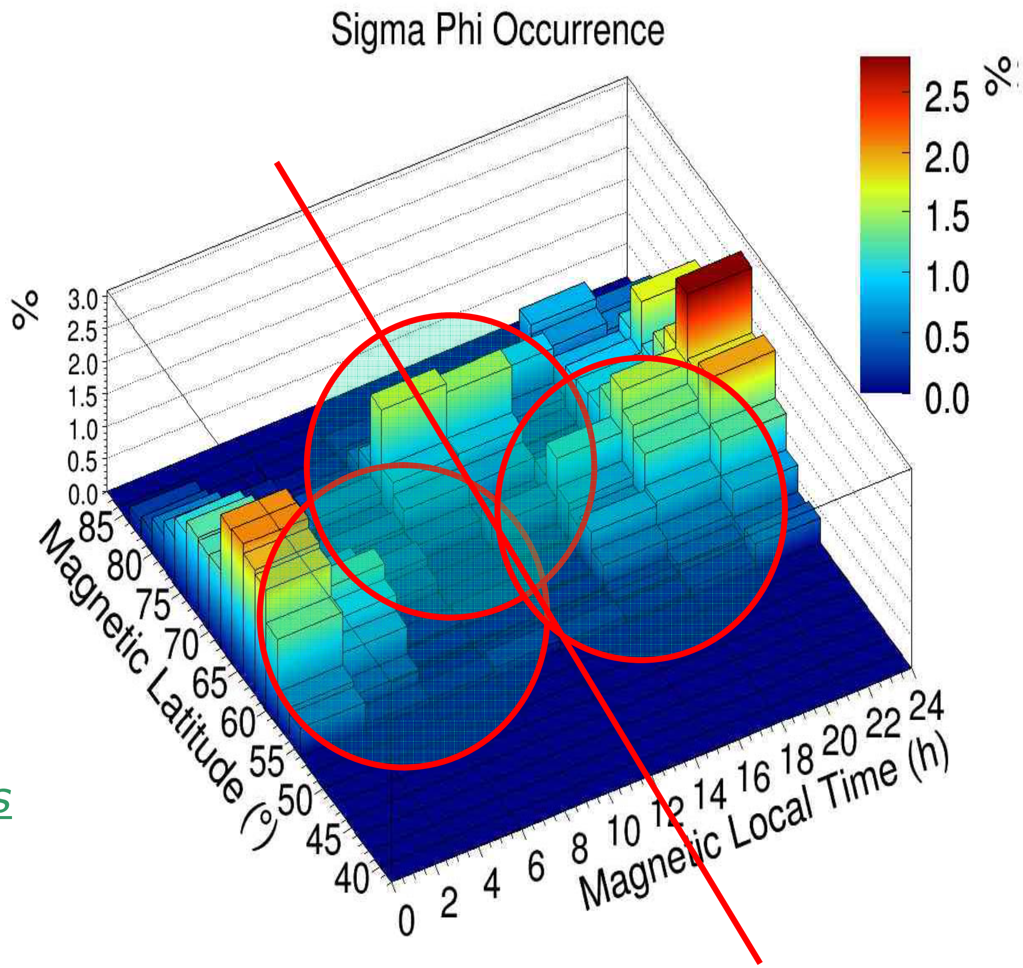
- All days maps
- Much more sensitivity to phase than to amplitude scintillation
  - Different scales!
- General behavior is significantly different
  - σ_φ: characterization both in Mlat and MLT
  - S_4: occurrence is confined in a well defined region (Midnight,65°)
- The <u>scale of the irregularities</u> can explain the difference
  - depends also on the anisotropy due to the irregularities field alignment
- *Dedicated paper is currently in preparation!*





σ_φ map

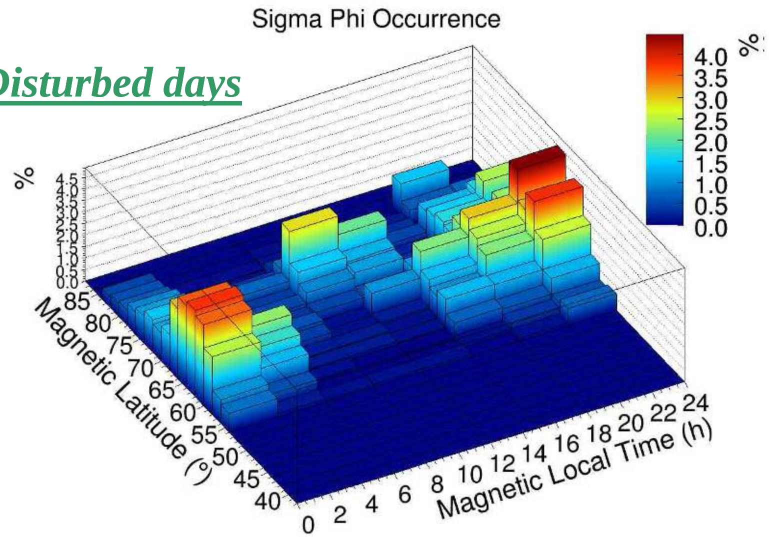
- 2 MLT regions:
  - midnight
  - noon
- Correspondence with the equator and poleward walls of the ***ionospheric troughs (?)***
  - Similarities with the troughs position
    - noontime → high latitudes
    - afternoon → migration toward lower latitudes
    - minimum early in the morning
    - asymmetry of the trough position around noon
- Asymmetry around midnight: ***polar cap patches (?)***
- Phase scintillation appears mostly due to the *electron density gradients*
- *TEC* distribution follows the position of the troughs and polar patches:
  - large gradients in the electron concentration.
- Accordingly with precedent studies (see References)



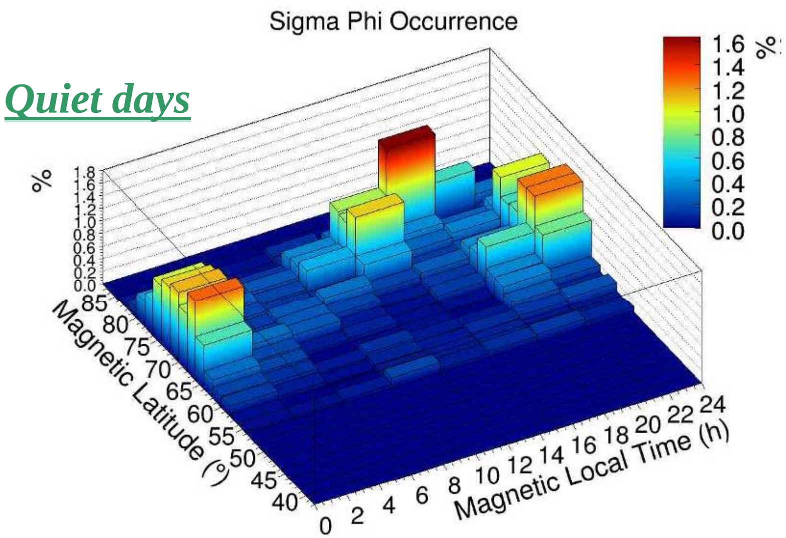
σ_φ quiet/dist. days maps

- Peak occurrence in the quiet days is of the same order of magnitude than in the disturbed
- ***Disturbed days***:
  - displacement of the auroral oval under disturbed conditions
  - displacement to lower latitudes of the scintillation occurrence in the post-midnight sector
- ***Quiet days***:
  - scintillation boundary follows closely the trough minimum in the pre-midnight sector
  - diverges during the post-midnight hours

Disturbed days



Quiet days



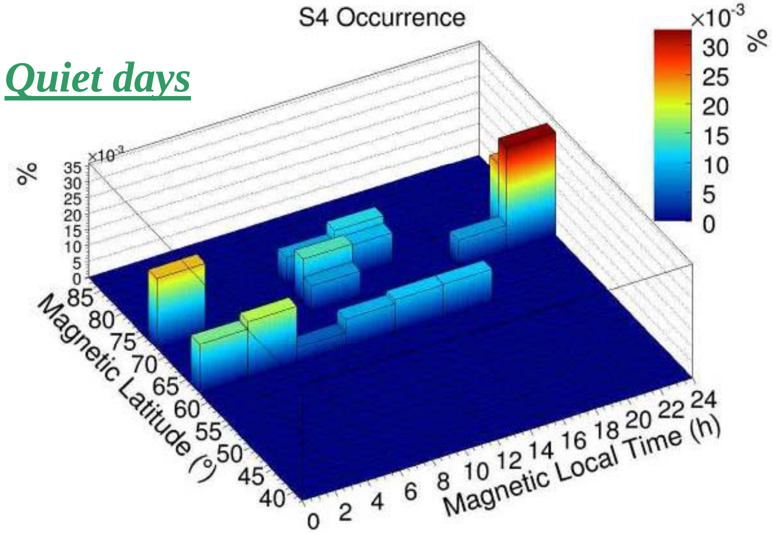
S_4 quiet/dist. days maps

- Peak occurrence in the quiet days is one order of magnitude smaller than in the disturbed
  – Differently from phase scintillation
- ***Quiet days***:
  – enhances at noon and midnight
  – scintillation area between 62° and 64° from midnight to 18 MLT:
    - co-located with the equatorward boundary of the auroral oval (?)
    - contribution from the BRO station
- ***Disturbed days***:
  – similar pattern for midnight and noon drifting to lower latitudes and extending from 16 MLT to 6 MLT
  – evident enhancement (62°-64° Mlat, noon)
    – BRO contribution

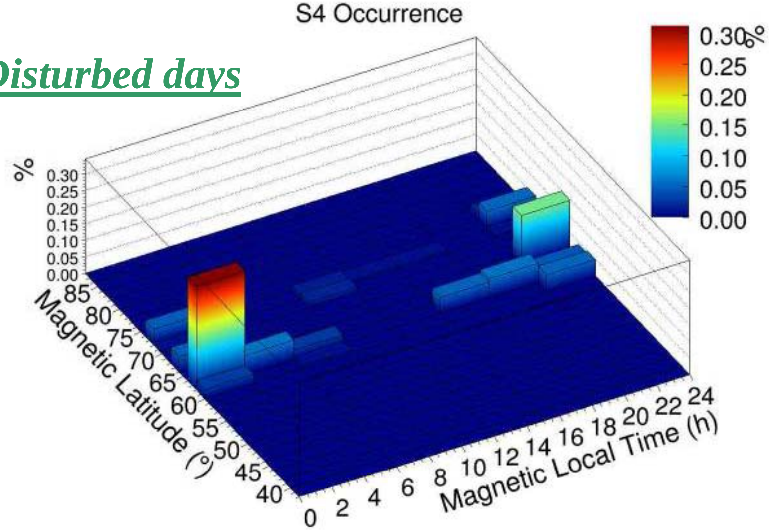
equatorward boundary of the auroral oval is a privileged site (amplitude scintillation)

- ***Open question***: Which is the role of the anisotropy?

Quiet days



Disturbed days



Remarks

- Characterization of the scintillation scenarios from *cusp/cap to sub-auroral regions* with MLT vs Mlat occurrence maps.
  - Original and novel statistics
  - Wide range of latitudes
- *Higher sensitivity to phase than to amplitude scintillation* of polar ionosphere.
- *Displacement of scintillation regions* towards lower latitudes during magnetically active periods.
- ***Phase scintillation maps***
  - Scintillation occurrence during the disturbed days larger than during quiet
    - but of the same order of magnitude.
  - Phase scintillation in terms of ionospheric troughs and polar cap patches position
- ***Amplitude Scintillation***
  - Disturbed days contribution is one order of magnitude larger than during quiet days
  - *Equatorward boundary of the auroral oval is a privileged site* to host irregularities causing amplitude scintillations

What's next

- *Contribution of the anisotropy* due to the irregularities field alignment is still under investigation (forthcoming dedicated paper)
- *Adding data* coming from other instruments improving the statistical analysis
  - SuperDARN
  - Ionosondes
  - …

Spogli et al. (2009) is ready for submission!

Thanks for your attention…

References

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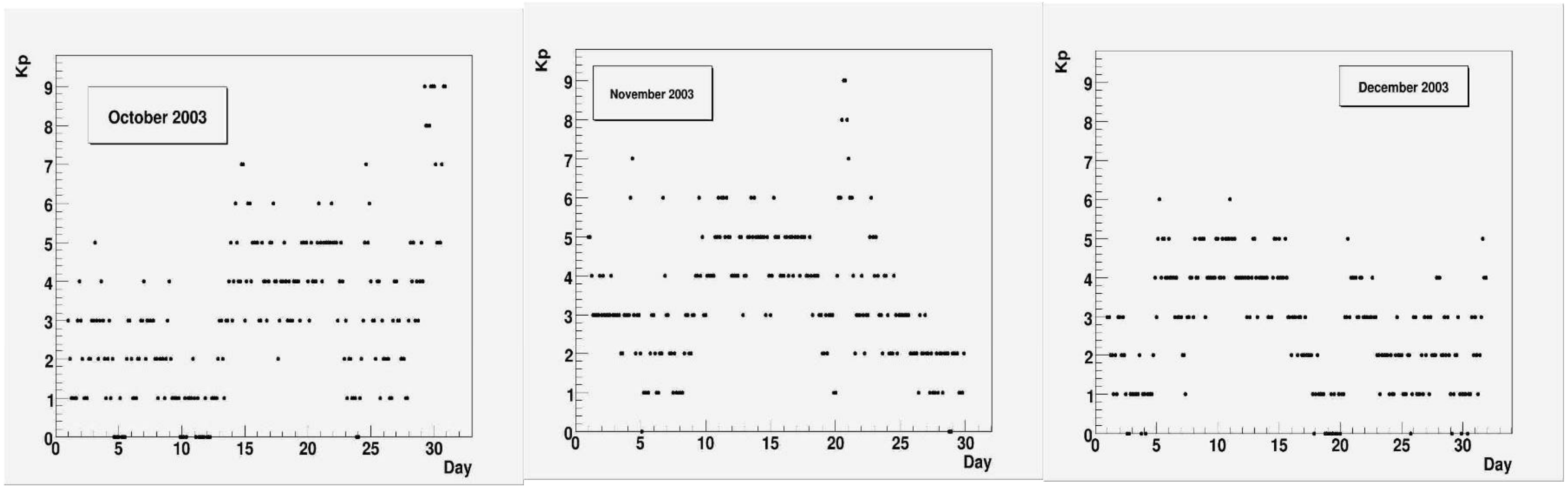
Backup slides

Introduction

- Under perturbed conditions coming from the outer space, the ionosphere may become highly turbulent and small scale irregularities (from centimeters to meters), typically enhancements or depletions of the electron density embedded in the ambient ionosphere, can form causing diffraction effects on the satellites signals passing through them. Such effect can abruptly corrupt the performance of the positioning systems and affect, in turn, the awareness and safety of the modern devices
- The fluctuations in the carrier frequency of the radio waves received at ground, commonly called ionospheric amplitude and phase scintillations, can be analyzed to investigate the physical processes causing them and, conversely, to understand how these processes affect the operational capabilities of GNSS receivers.

Geomagnetic Characterization

- 2 intense magnetic storms and important scintillation events occurred on 30-31 October and on 20-21 November 2003
- A day is assumed to be quiet if 50% of K_p values is less or equal to 4.
- According to this assumption, about half of the days in each month is found to be disturbed.



Variation of Kp index during October, November and December 2003

List of days

Date	Quiet/Disturbed
01/10/2003	quiet
02/10/2003	quiet
03/10/2003	disturbed
04/10/2003	quiet
05/10/2003	quiet
06/10/2003	quiet
07/10/2003	quiet
08/10/2003	quiet
09/10/2003	quiet
10/10/2003	quiet
11/10/2003	quiet
12/10/2003	quiet
13/10/2003	disturbed
14/10/2003	disturbed
15/10/2003	disturbed
16/10/2003	disturbed
17/10/2003	disturbed
18/10/2003	disturbed
19/10/2003	disturbed
20/10/2003	disturbed
21/10/2003	disturbed
22/10/2003	disturbed
23/10/2003	quiet
24/10/2003	disturbed
25/10/2003	quiet
26/10/2003	quiet
27/10/2003	quiet
28/10/2003	disturbed
29/10/2003	disturbed
30/10/2003	disturbed
31/10/2003	disturbed

Date	Quiet/Disturbed
01/11/2003	disturbed
02/11/2003	quiet
03/11/2003	disturbed
04/11/2003	disturbed
05/11/2003	quiet
06/11/2003	disturbed
07/11/2003	quiet
08/11/2003	quiet
09/11/2003	disturbed
10/11/2003	disturbed
11/11/2003	disturbed
12/11/2003	disturbed
13/11/2003	disturbed
14/11/2003	disturbed
15/11/2003	disturbed
16/11/2003	disturbed
17/11/2003	disturbed
18/11/2003	disturbed
19/11/2003	quiet
20/11/2003	disturbed
21/11/2003	disturbed
22/11/2003	disturbed
23/11/2003	disturbed
24/11/2003	quiet
25/11/2003	quiet
26/11/2003	quiet
27/11/2003	quiet
28/11/2003	quiet
29/11/2003	quiet
30/11/2003	quiet

Date	Quiet/Disturbed
01/12/2003	quiet
02/12/2003	quiet
03/12/2003	quiet
04/12/2003	quiet
05/12/2003	disturbed
06/12/2003	disturbed
07/12/2003	quiet
08/12/2003	disturbed
09/12/2003	disturbed
10/12/2003	disturbed
11/12/2003	disturbed
12/12/2003	disturbed
13/12/2003	disturbed
14/12/2003	disturbed
15/12/2003	disturbed
16/12/2003	quiet
17/12/2003	quiet
18/12/2003	quiet
19/12/2003	quiet
20/12/2003	quiet
21/12/2003	disturbed
22/12/2003	quiet
23/12/2003	quiet
24/12/2003	quiet
25/12/2003	quiet
26/12/2003	quiet
27/12/2003	quiet
28/12/2003	quiet
29/12/2003	quiet
30/12/2003	quiet
31/12/2003	quiet

Station (ID)	Geographic Latitude (G_{lat})	Geographic Longitude (G_{lon})	Corrected Geomagnetic Latitude (M_{lat})	Corrected geomagnetic longitude (M_{lon})	M_{lat} range
NYA	78.9°N	11.9°E	76.0°N	112.3°E	68°-84°N
HAM	70.7°N	23.7°E	67.2°N	108.0°E	58°-76°N
BRO	65.5°N	12.2°E	62.6°N	95.1°E	54°-72°N
NOT	52.9°N	1.2°W	54.8°N	87.1°E	40°-58°N

Table 1. Geographic (G_{lat},G_{lon}) and corrected geomagnetic (M_{lat},M_{lon}) coordinates together with the magnetic latitude range of the field of view of the GISTM receiver sites at 350 km.

Data

- Scintillation indices computed over 60 seconds
- Reducing tracking errors
  - $\alpha_{elev} > 15°$ for both indices.
- Vertical quantities:

$$\sigma_{\varphi}(\alpha_{elev} = 90^{o}) = \sigma_{\varphi}(\alpha_{elev})\sin^{0.5}(\alpha_{elev})$$

$$S_4(\alpha_{elev} = 90^{o}) = S_4(\alpha_{elev})\sin^{0.9}(\alpha_{elev})$$

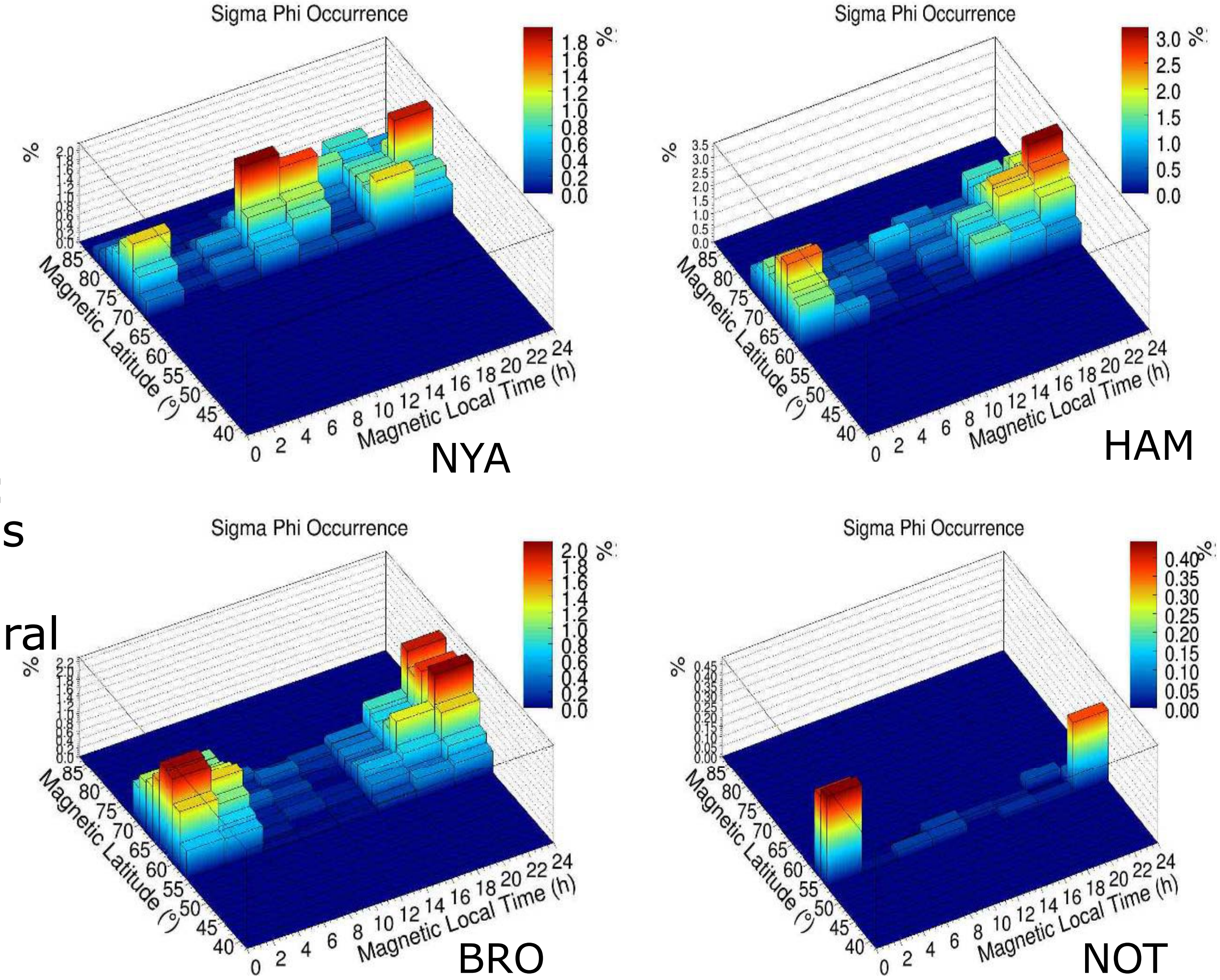
- the exponent of the phase is assumed to be 0.5, while the amplitude one depends on the spectral index of the phase scintillation spectrum, *p,* and on the irregularities anisotropy.
  - we assume p=2.6, corresponding to *b* equal to 0.9.

Total amount of data points is of the order of 1 million per station

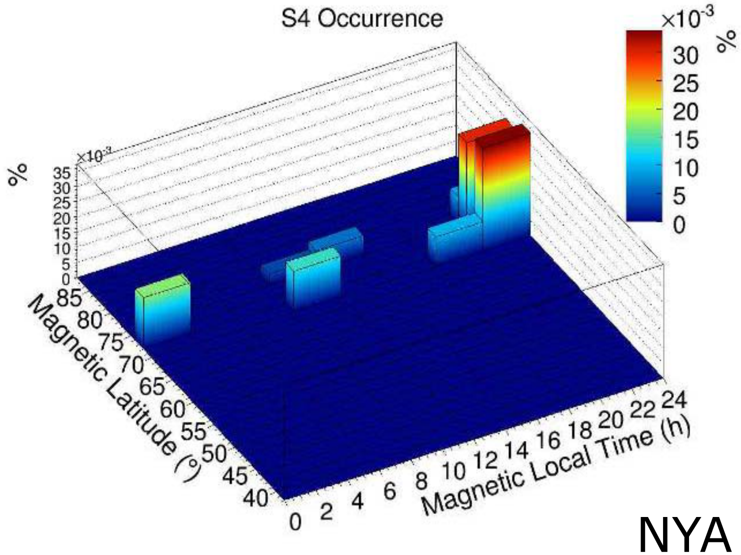
- Only a significant data gap in Dec in HAM and BRO

σ_φ single station maps

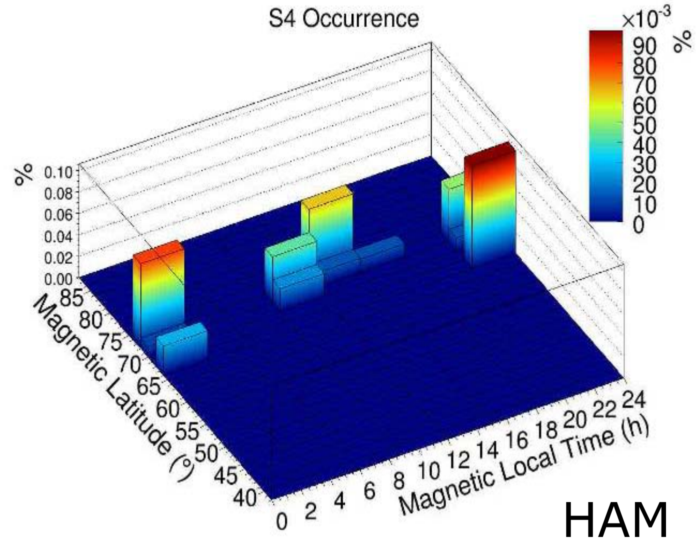
- All days
- NYA: cusp/cap contribution
- HAM and BRO: auroral stations
  - No noon
- NOT: sub-auroral



S_4 single station maps

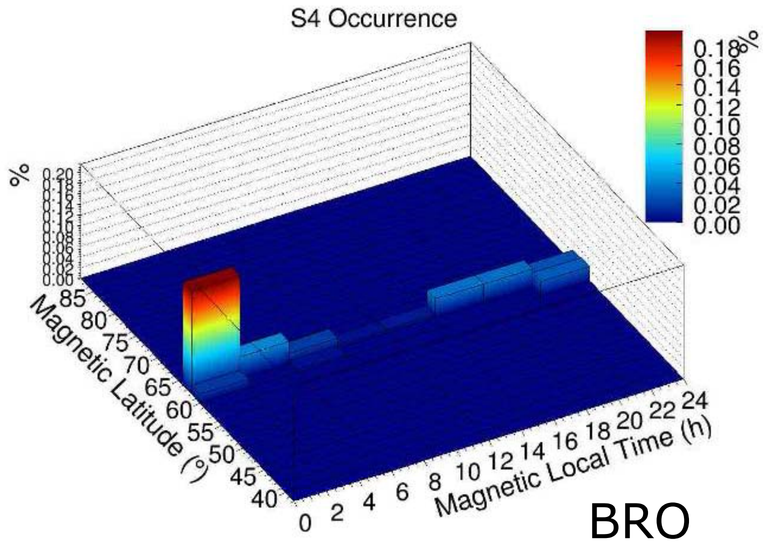


NYA



HAM

- All days
- NYA and HAM: noon and midnight enhancement
  - Differently from phase
- BRO: Midnight enhancement at lower latitudes
- NOT: no contributions (0%)



BRO

Overview and Remarks (III)

- Observation of the contribution of the four receivers separately:
  - NYA (cusp) → cusp/cap noon effect
  - HAM and BRO (auroral) → enhancement of the occurrence at midnight and asymmetry towards afternoon
  - NOT (mid-lat) → little contribution
- Observation of the contribution of the four receivers separately:
  - NYA and HAM → enhancements at noon and midnight
  - BRO → midnight enhancements only
  - NOT → no contributions

Data

- **Phase scintillation index σ_{Φ}**
  - standard deviation of the detrended phase of the carrier frequency over a certain interval (60 s).
  - Measured in radians
- **Amplitude scintillation index S_4**
  - standard deviation of the received power normalized by its mean value.

$$S_4^2 = \frac{\left\langle I - \langle I \rangle \right\rangle^2}{\langle I \rangle^2}$$

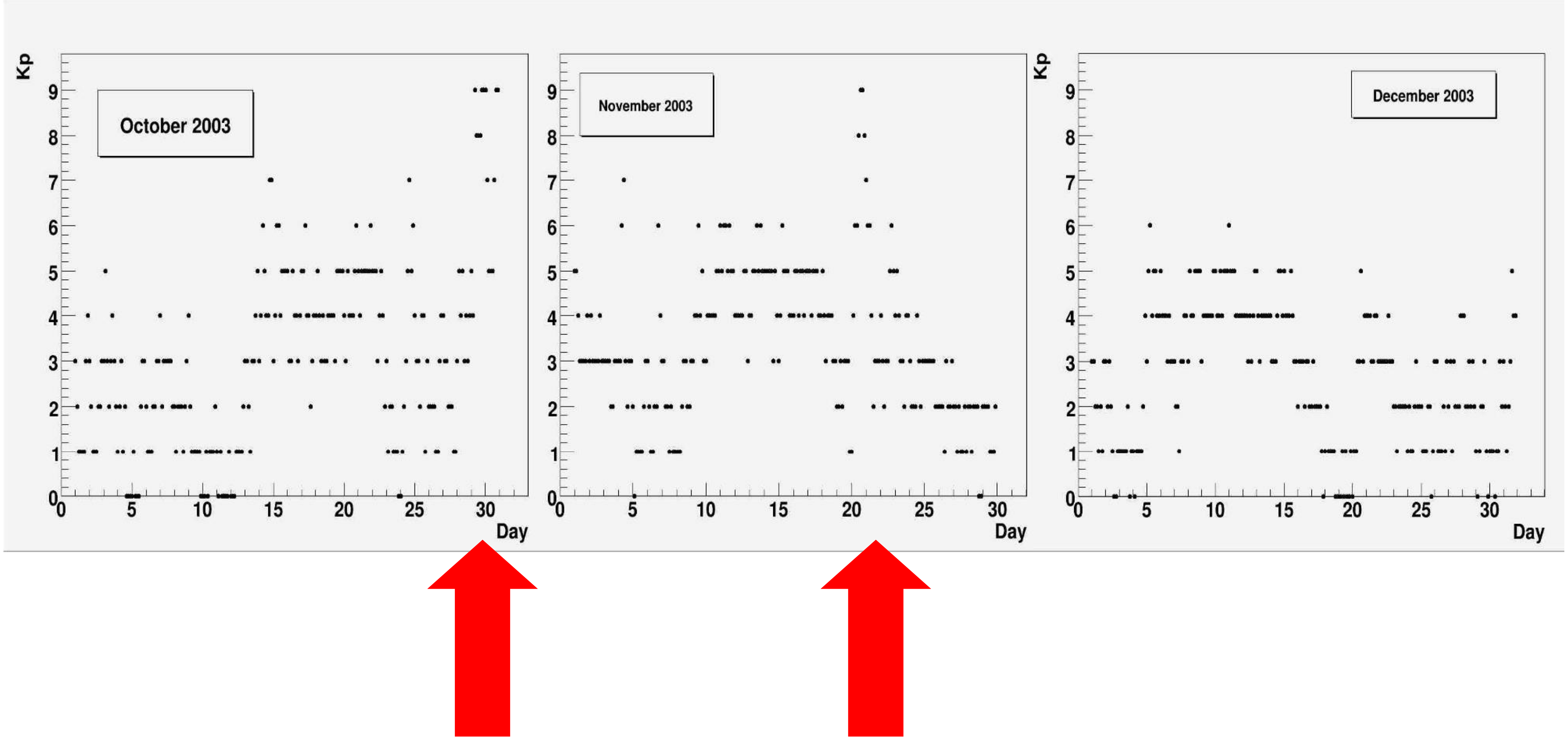
- **Total Electron Content**
  - The electron density is obtained by counting the number of electrons in a vertical column with a cross-sectional area of 1 m^2, extending from the GPS satellite to the observer.
- **Cut on satellite elevation**
  - Elevation > 15 degrees
  - Avoid error sources (multipath, reflections, etc.)

Kp index

- Disturbances in the horizontal component of Earth's magnetic field
  - Maximum fluctuations observed on a magnetometer during a 3-hour interval
- Quiet/Disturbed day definition
- Data from World Data Center for Geomagnetism of Kyoto
  - http://swdcwww.kugi.kyoto-u.ac.jp/index.html
  - 3-hourly measurements of Kp for each day
    - 8 values per day
- Day is considered quiet if:
  - 50% of Kp values for that day is <= 4

Definition needs refining

Kp index


Kp
October 2003
November 2003
December 2003
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
Day

Ionospheric trough

The high latitude trough is a depression in ionization

- Occurring mainly in the night-time sector
- Most evident in the upper F-region
- It extends from 2 to 10 degrees equatorward of the auroral oval.
- The latitudinal boundaries of the trough may be sharp, especially the poleward boundary with the auroral oval.
- The ionospheric trough is representative of a number of anomalous features that are associated with phenomena around the polar regions.